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## THE PARRAY AS AN ACOUSTIC SENSOR

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THE PARRAY AS AN ACOUSTIC SENSOR

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## ABSTRACT

A parametric acoustic receiving array (PARRAY) can be narrowly defined as
the volumetric, virtual array synthesized in the water volume between two high
frequency transducers, called the pump and the hydrophone. It is instructive,
however, to generalize the concept to include the high frequency transducers
and associated pump signal generation and receiving electronics since the
PARRAY is then analogous to a conventional acoustic sensor. Selection of opti-
mum parameters for the generalized PARRAY is complicated by the fact that the
basic parameters are not independent; however, by requiring that the total
self-noise output of the PARRAY be minimized, one can develop systematic proce-
dures for selecting optimum values for the basic parameters within the con-
straints of existing engineering technology. It follows that implementation
of a practical and useful PARRAY for reception of low frequency acourtic
signals in the ocean requires not only careful selection of system parameters
but also careful design of electronic subsystems which must satisfy stringent
performance requirements. To investigate the importance of the various parame-
ters, a PARRAY with a 340 m pump-hydrophone separation was installed in the
45 m deep, freshwater environment of Lake Travis, TX, USA. Measurements were
obtained over the 35 to 800 Hz frequency range demonstrating that the self-
noise of the experimental PARRAY was below the ambient noise level in that
environment. The experimental PARRAY is described and test results are
presented and discussed.

## I.  INTRODUCTION

The parametric acoustic receiving array (PARRAY) exploits the inherent
nonlinearity in the pressure-density relationship of water to achieve direc-
tional reception of low frequency acoustic waves with two small, high fre-
quency transducers and some associated electronics. This possibility was
suggested by Westervelt and, shortly thereafter, experiments were designed and
conducted to demonstrate the phenomenon [1-4]. A number of theoretical and
experimental investigations followed. Most of these investigations emphasized
demonstrating the phenomenon under various conditions and developing and
validating mathematical models to describe the basic physics of the process
[5-12]. Beam patterns were obtained and the acoustic pressures of the inter-
action components were measured. Typical of basic measurements using readily
available laboratory equipment, the received low frequency signals were of
relatively high amplitude to assure adequate signal-to-noise ratios for relia-
ble measurements.

It was recognized, however, that if parametric reception of sound were to
progress from the status of an academic novelty to a useful tool for underwater
acoustic measurements, systematic methods would have to be developed to select
optimal parameter values within the constraints of existing engineering

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technology.  This problem was addressed in studies conducted at Applied Research Laboratories, The University of Texas at Austin (ARL:UT) [13-15].  The selection of optimal parameter values has also been discussed by McDonough [16].  Two factors not considered by McDonough will be discussed later in the paper.

In the ARL:UT studies, techniques and analytical models were developed to permit selection of optimal parameter values within the constraints of existing electronics and transducer technology.  Four major areas of technology were identified in which significant advances in the state of the art were required. As a result of these studies, a program to develop advanced hardware for parametric reception of low audio frequency signals produced by ocean shipping was initiated at ARL:UT.  The effort was structured as an integrated program of analysis, experiments, hardware design, fabrication, lake testing, and sea testing.  The results of that program through the tests at Lake Travis, Texas, are summarized in this paper.

## II.  DESCRIPTION OF THE PARRAY

A PARRAY can be narrowly defined as the volumetric, virtual array synthesized in the water volume between two high frequency transducers.  It is instructive, however, to generalize the concept to include the pump signal generation and receiving electronics as well as the high frequency transducers. Thus generalized, the PARRAY is analogous to a conventional acoustic sensor.

The basic elements of the PARRAY and its operation are illustrated schematically in Fig. 1.  A continuous, high frequency acoustic wave, symbolized by the closely spaced, concentric arcs, is projected from one of the transducers (pump) to the second transducer (hydrophone), which is located a distance L from the pump. An ambient, low frequency acoustic wave propagating through the area, represented by the widely spaced diagonal lines, will interact non-linearly with the pump wave to generate intermodulation products.



Fig. 1.  PARRAY Functional Diagram

Different ambient low frequency signals will also interact nonlinearly with each other to generate intermodulation products.  However, because the ambient signals are much lower in amplitude and frequency than the pump signal, inter-modulation products generated by interactions of the ambient signals can be neglected.

The pump oscillator and power amplifier generate the high frequency pump signal and amplify it to a level sufficient to produce the desired pump acoustic signal level in the water.  The function of the receiver electronics is to recover the ambient signals by demodulating the interaction products which appear as modulation sidebands on the pump carrier.  Thus an ambient acoustic signal of frequency $f_s$ produces an electrical signal which is also of frequency $f_s$ at the output of the receiver electronics.
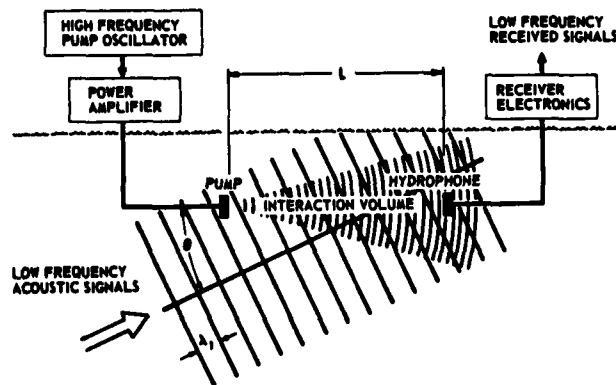
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Consider now a generic acoustic sensor as shown in the block diagram in Fig. 2. The fundamental purpose of an acoustic sensor is to produce an electrical analog output signal in response to an acoustic input signal. Thus an acoustic sensor has a sensitivity, usually expressed as the ratio of open circuit voltage output to the acoustic pressure input. It has a directional response function, which includes the possibility that the response is omnidirectional. Generally one requires that an acoustic sensor be linear in the mathematical sense that an increase in acoustic pressure produces a proportional increase in output voltage. Furthermore, an acoustic sensor will have some noise floor which represents the noise pressure equivalent to the internal, or self-noise, sources. In conventional acoustic sensors, the noise floor will be determined by the internal resistance and electroacoustic efficiency of the sensor.

ACOUSTIC SENSOR

| | HYDROPHONE SENSITIVITY |
| | DIRECTIONAL RESPONSE - DIRECTIVITY |
| INPUT SIGNAL | LINEARITY |
| | NOISE FLOOR - SELF NOISE |
| | IMPEDANCE |
| ACOUSTIC | EFFICIENCY |

OUTPUT SIGNAL
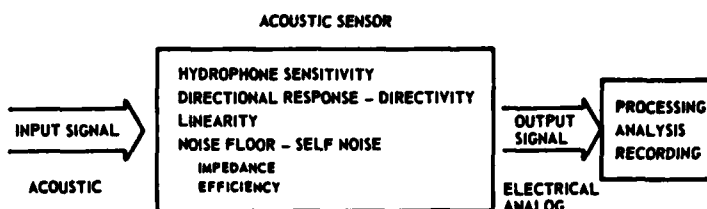
PROCESSING
ANALYSIS
RECORDING

ELECTRICAL ANALOG

Fig. 2. Functional Diagram of Generic Acoustic Sensor

An analysis of the generalized PARRAY shows that it satisfies the basic requirements of an acoustic sensor. This analysis also demonstrates that the critical factor for practical utilization of the PARRAY to receive low frequency acoustic signals in the ocean is self-noise of the PARRAY.

The acoustic sensitivity of the PARRAY illustrated in Fig. 1 can be calculated from previous work. Berktay and Muir define the "relative acoustic sensitivity" of a PARRAY, $s_r$, as the ratio of the amplitude of the interaction component to that of the incident signal wave [8]. If G is the transfer function of the receiver electronics with source impedance equivalent to that of the hydrophone and M is the voltage sensitivity of the hydrophone at the same impedance level, then the voltage sensitivity of the PARRAY is given by

$$M_p = s_r MG \qquad . \qquad (1)$$

Using the axial value of $s_r$ from Berktay and Muir, this becomes

$$M_p = GM(\omega_p \pm \omega_s)\beta P_1 \exp(-\alpha_\pm L)/\left(2\rho_o c_o^3\right) \qquad (2)$$

where

$\omega_p$, $\omega_s$ are the angular frequency of the pump and signal, respectively,

$\rho_o$, $c_o$ are the static density and small signal sound velocity of the medium respectively,

$P_1$ is the pump pressure amplitude at a distance of 1 m from the pump,

$\beta$ is the coefficient of nonlinearity of the medium, approximately equal to 3.5 in water,

$\alpha_\pm$ is the small signal absorption coefficient at the frequency $\omega_p \pm \omega_s$, and

L is the pump-hydrophone separation.

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The phasing of the interaction between the pump and signal waves of the PARRAY is a function of the plane angle, $\theta$, between the propagation vectors of the pump and signal waves. The maximum response of the synthesized array is obtained when the pump and signal waves are propagating in the same direction; hence the maximum response axis (MRA) of the PARRAY is in the direction of a line extending from the hydrophone through the pump. Although the array synthesized in the interaction volume is actually a volumetric array, the directivity characteristics of the synthesized array are similar to those of a continuous, end-fire array of length L. It is this end-fire array effect that provides the directivity of the PARRAY and hence its ability to discriminate against the low frequency ambient noise that otherwise masks the signal wave.

Using the same notation as above, the directional response of the PARRAY is given by [4,5]

$$D(\theta) = \frac{\beta - (1-\cos\theta)}{\beta} \frac{\sin[(kL/2)(1-\cos\theta)]}{(kL/2)(1-\cos\theta)} \quad , \tag{3}$$

where k is the acoustic wave number of the signal to be detected.

The directional response of the PARRAY is symmetric about the line joining the pump and hydrophone, i.e., the PARRAY has a conical beam pattern. The half-power beamwidth of the PARRAY, in degrees, is given approximately by

$$\theta = 105 \sqrt{\lambda/L} \quad , \tag{4}$$

where $\lambda$ is the acoustic wavelength of the signal to be detected. From this we see that large pump-hydrophone separations would be required to obtain beamwidths of a few degrees at low audio frequencies. This fact is noted by McDonough; however, he overlooked the work of Berktay and Muir in beamforming and beamsteering arrays of PARRAYs.

The detection of low frequency signals from a distant source is closely related to the ability of the acoustic sensor to discriminate against low frequency ambient noise and thus to improve the signal-to-noise ratio (S/N) compared to a simple, omnidirectional sensor. Although the ambient noise field is rarely isotropic, the directivity index (DI) is a convenient and useful measure for first order comparisons of different acoustic sensors. For large acoustic apertures, the DI of the PARRAY is given by

$$DI = 10 \log(4L/\lambda) \quad . \tag{5}$$

The front-to-back ratio (F/B) of the PARRAY is also a function of the acoustic aperture. For kL>1, the ratio of the maximum response of the PARRAY to the envelope of the back lobes is given by (in decibels)

$$F/B_{dB} = 20 \log(7kL/3) \quad . \tag{6}$$

It should be noted that both the DI and the F/B of the PARRAY are functions of the acoustic aperture and hence do not depend upon the pump frequency.

The linearity of the PARRAY as an acoustic sensor is evident from Eq. (2) if the basic parameter values are not changed. Naturally, the signal wave amplitude must be above the self-noise of the PARRAY.

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Since the interaction components are very low level signals, the self-noise
components of the PARRAY must be maintained at low levels if a S/N improvement
commensurate with the directivity characteristics of the PARRAY is to be
realized.  The principal noise sources in the PARRAY, illustrated schematically
in Fig. 3, are:

> (1)  low frequency ambient noise
> (2)  pump frequency ambient noise
> (3)  pump electronic noise
> (4)  pump and hydrophone vibration
> (5)  receiver electronic noise
> (6)  pump-boundary interaction
> (7)  pump interaction with medium inhomogeneities.

The effects of the first listed
source, low frequency ambient
noise is determined by the direc-
tional characterisitcs of the
PARRAY in the same manner as for
any other acoustic sensor.  The
effects of the remaining listed
sources are determined by the
construction and operating
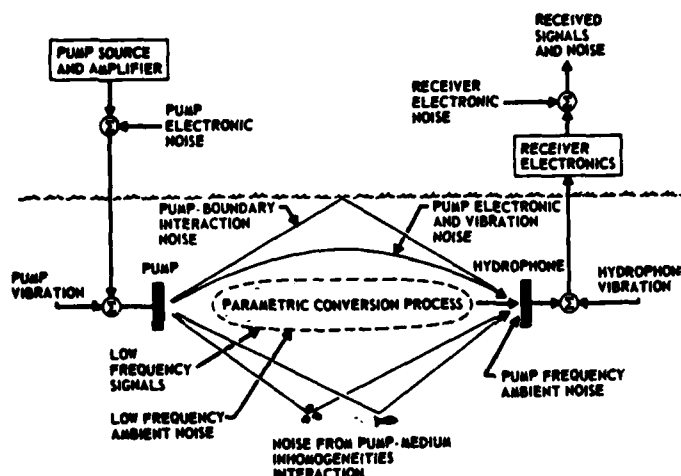parameters of the PARRAY.



Fig. 3.   Sources of Noise in a PARRAY

III.  PARAMETER SELECTION PROCEDURES

Selection of optimal parameter values for a PARRAY is complicated by the fact
that the parameters are not independent.  Selection procedures will vary some-
what depending upon the intended use, range of signal frequencies to be received,
whether it is to operate in the ocean or in fresh water, depth of the water,
the depth at which the PARRAY is to operate, and other factors.  The present
analysis incorporates the following assumptions about these factors.

We will consider a large aperture PARRAY to receive low frequency signals
from distant shipping at sea.  Thus the signal frequencies will be below 1 kHz
and a large acoustic aperture will be required, i.e., $kL>>1$.  We will further
assume that the nearfield distance of the pump is small compared to the pump-
hydrophone separation L.

In the parameter selection process one must recognize that if we are to
obtain the maximum increase in S/N commensurate with the directivity character-
istics of the PARRAY, then the equivalent noise pressure of the PARRAY must be
reduced to less than the ambient noise within the PARRAY beam.  To provide a
method of evaluating tradeoffs in the parameter values, we will develop an

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expression for the equivalent noise pressure of the PARRAY, i.e., the low frequency plane wave noise equivalent to the self-noise of the PARRAY. We will not consider the last two listed noise sources since analytic expressions for the effects of pump interactions with boundaries and inhomogeneities in the medium are not available. These effects can be included when suitable mathematical models are developed.

Noise due to the pump signal source was mentioned by McDonough [16] but it was not included in his analysis. Ideally, the pump signal is a pure sinusoid of frequency $f_p$; however, physical oscillators always have noise at sideband frequencies. The level and characteristics of this sideband noise are dependent upon the quality of the signal generation equipment. The equivalent plane wave noise pressure at the input to the PARRAY at frequency $f_s$ due to the sideband noise of the pump source is given by

$$N_p = (q_s P_1 / s_r L) \exp(-\alpha_\pm L) \qquad (7)$$

where $q_s$ is the ratio of the sideband noise (measured in a 1 Hz bandwidth about the frequency $f_p \pm f_s$) to the amplitude of the pump frequency signal.

The noise due to internal sources in the receiver electronics competes with the desired signals from the interaction process. The contribution to the plane wave noise pressure at the input to the PARRAY due to these receiver internal noise sources is

$$N_e = V_{es} / (M s_r) \qquad (8)$$

where $V_{es}$ is the equivalent input noise of the receiver electronics, in $V/\sqrt{Hz}$, at the frequency $f_p \pm f_s$ when the receiver is driven with a source impedance equivalent to the hydrophone.

Acoustic ambient noise at frequencies near the pump frequency also enters the hydrophone and competes with the interaction components due to the signal wave. This acoustic ambient noise in the pump frequency region is the incoherent sum of noise from many sources, e.g., thermal agitation of the water molecules, wind generated surface wave motion, and biological sources such as snapping shrimp and cetaceans. Since noise from biological sources is highly variable and dependent upon geographic location, a survey of the high frequency ambient noise is desirable before a PARRAY is installed. Because of the variability and dependence upon location, we will not include biological noise sources in the present analysis.

The effect of thermal agitation and wind generated wave motion can be quantified and included in the analysis. The wind dependent ambient noise decreases with increasing frequency at approximately 5 dB per octave. The Knudsen noise pressure spectrum due to wind generated surface wave motion at the frequency f can be represented by the empirical equation

$$N_w = 0.063 \ (SS+1)^{3/2} f^{-5/6} \quad , \qquad (9)$$

where SS is the sea state and the frequency is in hertz. In general, the wind dependent noise is anisotropic and depth dependent; however, at shallow depths we will assume that the wind dependent noise is approximately isotropic.

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The noise pressure due to thermal agitation of the water molecules has been shown by Mellen [17] to be represented by

$$N_t = \left(4\pi\rho_o KT/c_o\right)^{1/2} f \quad , \tag{10}$$

where K is Boltzman's constant, T is temperature in degrees Kelvin, and f is the frequency in hertz.

The pump frequency acoustic ambient noise pressure is the incoherent sum of $N_w$ and $N_t$ and the equivalent plane wave noise pressure at the face of the hydrophone is obtained by dividing this sum by the square root of the directivity factor of the hydrophone. Thus the equivalent plane wave noise pressure at the input to the PARRAY due to pump frequency ambient noise is

$$N_{pa} \approx \frac{1}{s_r} \left[\frac{N_w^2 + N_t^2}{d}\right]^{1/2} \quad , \tag{11}$$

where d is the directivity factor of the hydrophone.

The response of the PARRAY to transducer vibration is significantly different from the response of conventional hydrophones and arrays. The response of the PARRAY to motion of the pump and hydrophone has been investigated analytically and experimentally [18]. Relative motion of the pump and hydrophone induce Doppler modulation of the pump wave and produce modulation sidebands that are indistinguishable from those produced by interaction of the pump wave and an acoustic signal wave. If $A_s$ is the composite acceleration of the pump and hydrophone at the frequency $f_s$, then it can be shown that the equivalent plane wave noise pressure at the input to the PARRAY due to this transducer motion is

$$N_v = \rho_o c_o^2 A_s / 4\beta L\pi^2 f_s^2 \quad . \tag{12}$$

By composite acceleration we mean the coherent sum of the pump and hydrophone accelerations in an inertial frame of reference.

Since the noise sources discussed in the preceding paragraphs are incoherent, the total equivalent noise pressure at the input to the PARRAY due to these noise sources is obtained from the incoherent sum of $N_e$, $N_p$, $N_{pa}$, and $N_v$ as

$$\Sigma N = \left[N_e^2 + N_p^2 + N_{pa}^2 + N_v^2\right]^{1/2} \quad . \tag{13}$$

The expression for the equivalent noise pressure provides a connection between the parameters of the PARRAY. In practice, one selects the pump-hydrophone separation required to yield some desired beamwidth and DI and within physical constraints. The remaining parameter values are selected to minimize the PARRAY self-noise. Equation (13) permits the improvement or degradation in self-noise caused by changes in parameter values to be evaluated.

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## IV. HARDWARE DEVELOPMENT

The goal of our program has been limited to demonstration of PARRAY technology for pump-hydrophone separations of a few hundred meters. An investigation was performed to define the parameter values required for a low self-noise PARRAY of this length. This study showed that improvements in hardware were required in several areas. A hardware development program was initiated which yielded state of the art advances in four major hardware areas: high spectral purity pump signal generation; commensurate power amplification; high efficiency, high power transducer element and array design; and detection of sideband signals with very small modulation indices.

As a result of the nonlinear mixing process in the water, the information in the low frequency signal wave appears as low level, modulation sidebands of the pump (carrier). The function of the receiving electronics is to suppress the high level pump signal while simultaneously amplifying and detecting the low level near-sideband signals. In principle, this is a straightforward signal processing problem commonly encountered in communications. The difficulty, however, arises from the fact that the sideband signals, which may be only 50 to 100 Hz away from the 65 kHz pump frequency, are 140 to 160 dB below the level of the pump frequency signal. We chose the direct approach of crystal band elimination filters to suppress the pump signal [19]. A band elimination processor was developed that is capable of detecting signals with carrier to sideband ratios approaching 180 dB.

A block diagram of the band elimination receiver is shown in Fig. 4. Cascaded crystal filters and low noise amplifiers provide the high order pump suppression and sideband signal amplification. The double sideband, suppressed carrier signal from the last filter and amplifier stage is coupled into a pair of balanced modulators operating in phase quadrature. A phase locked loop (PLL) oscillator provides the phase quadrature reference signals to the balanced



Fig. 4. Block Diagram of Band Elimination Receiver

modulators. The PLL oscillator reference may be supplied by an internal crystal controlled 65 kHz oscillator, an external reference oscillator, the pump signal source, or the pump frequency carrier from the hydrophone. The signals from the balanced modulators are low pass filtered, phase shifted by quadrature phase shifters, and summed with appropriate polarities to simultaneously yield the upper and lower sideband signals.

The input impedance of the first crystal filter is 15 kΩ in the passband and the insertion loss is 2 dB. Equivalent input noise of the band elimination receiver was measured at -152 to -151 dB re 1 V/$\sqrt{\text{Hz}}$ which is equivalent to a noise figure of 4 to 5 dB at the 15 kΩ input impedance. The input impedance of the receiver in the rejection band is on the order of 300 Ω. This implies a

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maximum carrier level of about +29 dB re 1 V at the output of the hydrophone impedance matching network since 1 mW is the maximum power that can be safely dissipated in the crystal filter. The combination of a -151 dB re 1 V/√Hz noise floor and a maximum input of +29 dB re 1 V yields a maximum carrier to sideband ratio of 180 dB.

Spectral purity of the pump signal is one of the most critical parameters of the PARRAY. Since oscillators with adequate spectral purity were not available commercially, a crystal controlled 65 kHz pump signal source was developed for the experimental PARRAY [15,20]. A spectrum level sideband noise 173 dB below the carrier level was achieved. This spectral purity represents a 40 dB improvement in sideband noise compared to that of oscillators available at the beginning of the program.

A schematic diagram of the pump signal source is shown in Fig. 5 and while the circuit appears uncomplicated, each component must be seiected for low noise characteristics. The signal source consists of three basic parts: a crystal controlled oscillator, an automatic gain control (AGC) circuit, and a buffer amplifier. The oscillator is a modified Pierce design of the emitter coupled type. The AGC maintains the crystal drive power in the region where minute changes will not generate phase modulation. The capacitor shown at the base of the crystal is used to provide increased voltage from the oscillator stage to drive the boot strap source follower isolation amplifier.
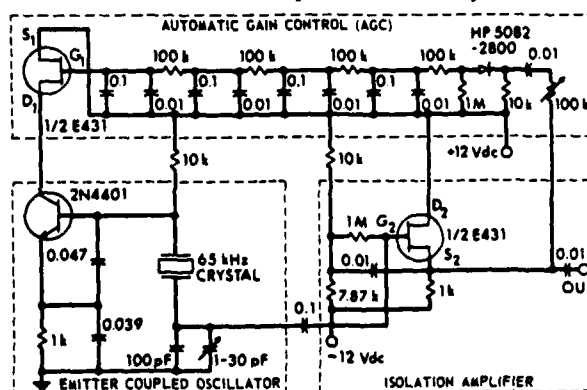


Fig. 5. Schematic Diagram of Crystal Controlled Pump Signal Source

The signal from the pump signal source was impedance matched to the band elimination receiver which was used to measure the sideband noise of the pump signal source. The results of this measurement are shown in Fig. 6. The carrier level at the output of the impedance matching network was +17 dB re 1 V. The upper curve is the sum of sideband noise from the signal source and internal noise from the band elimination receiver. The curve labeled "Receiver Noise" is the equivalent input noise of the band elimination receiver referenced to the input carrier level. It is clear that for this carrier level, the receiver noise is a significant contributor to the total sideband noise observed. The smooth curve is the pump signal source sideband noise (referenced to the carrier level) inferred from the measured
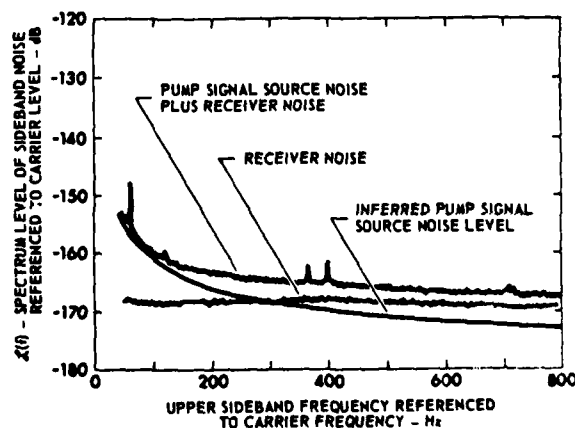


Fig. 6. Upper Sideband Noise of Pump Signal Source and Electronic Noise of Band Elimination Receiver

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noise levels under the assumption that the signal source and receiver noise sources are incoherent.

The inferred noise data from Fig. 6 are shown in Fig. 7 on a log frequency scale to more clearly display the character of the sideband noise. It may be



Fig. 7. *Sideband Noise of Pump Signal Source Illustrating Frequency Dependence*

seen that from 40 to 180 Hz the oscillator noise has a slope of $f^{-2}$ whereas from 180 to 700 Hz the slope of the noise is $f^{-1}$. Above 700 Hz the noise level is independent of frequency at -173 dB referenced to the carrier level.
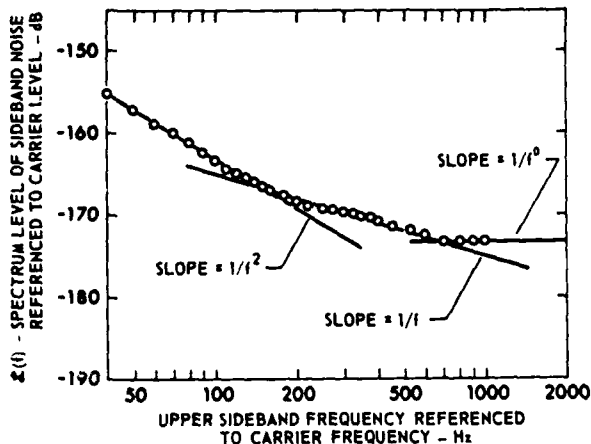
At the start of the PARRAY development program, a power amplifier for the pump signal was one of the biggest uncertainties. Manufacturers were not prepared to answer questions about the noise in the near sidebands of a high level signal. Starting with a basic design by Instruments, Inc., of San Diego, CA, for a 250 W class B power module, a pump power amplifier was developed and interfaced to the pump signal source. Measurements with this 250 W power amplifier demonstrated that spectrum level sideband noise from the amplifier is 168 dB below the carrier level when the amplifier is delivering 250 W into a resistive load at the carrier frequency. Similar results were obtained with the amplifier driving the PARRAY transducer.

The development of high efficiency transducers that can handle the high level CW pump signal was a significant achievement of the program [15,21,22]. These transducers exhibit good sidelobe behavior and do not introduce spurious sideband noise at higher power levels. The high electrical to acoustical conversion efficiency of these transducers is especially important in nonlinear acoustic applications. The design of these transducer elements is shown in Fig. 8. The
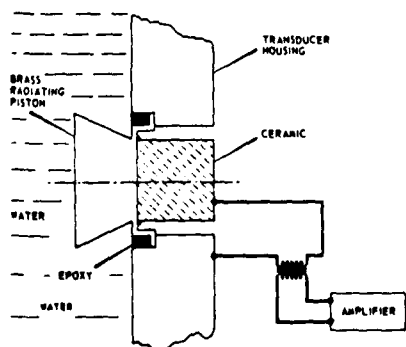


Fig. 8. Exposed Piston Transducer Structure with Rigidly Mounted Element and Epoxy Seal

conical radiating piston and integral mounting flange are machined on a turret lathe and bonded to the quarter-wavelength ceramic cylinder with quick setting epoxy. The element is attached to the transducer housing by filling the annular groove around the base of the radiating piston. Since the element is supported at a vibrational node and the ceramic is surrounded by air, there is very little internal dissipation of energy. Efficiency measurements are always suspect but based upon measurement of the quality factor of the element in air and in water, the electrical to acoustical efficiency appears to be greater than 90%. Arrays with up to

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432 elements of this type have been constructed and operated.

## V.   EXPERIMENTAL PARRAY MEASUREMENTS

The hardware described in the previous section was installed in a freshwater lake near Austin, Texas, to form an experimental 340 m PARRAY [23].   Experiments were performed under various conditions to investigate the self-noise and spatial processing gain.   In addition, a 5 m PARRAY was instrumented to measure the effect of transducer vibration on the PARRAY.

The geometry for experiments with the 340 m PARRAY is shown in Fig. 9, which is a topographic map of the lower portion of Lake Travis.   The lake is formed by Mansfield Dam, a large concrete structure containing a hydroelectric plant.   Three turbine generators are located at the site labeled "Powerhouse" on the map.   The elevation contours are labeled in feet above mean sea level and, as noted on the figure, normal lake level is 681 ft (207.6 m). Lake level at the time of the experiments was near normal.   The PARRAY transducers were located on two towers, denoted "West Tower" and "East Tower" in



Fig. 9.   Topography of Lower Lake Travis Showing Location of 340 m PARRAY and Experiment Geometry

Fig. 9, separated by 340 m.   The transducers are cabled back to the PARRAY electronics console located on the NAVSEA Barge.   The PARRAY pump was located on the east tower and the PARRAY hydrophone was mounted on the west tower. Thus, the MRA of the PARRAY was along the dashed line, denoted "PARRAY Axis," from the west tower to the east tower at a bearing of 068° magnetic.   The towers are set in approximately 46 m of water with the PARRAY transducers located 24 m above the lake bottom, or near middepth at those points.
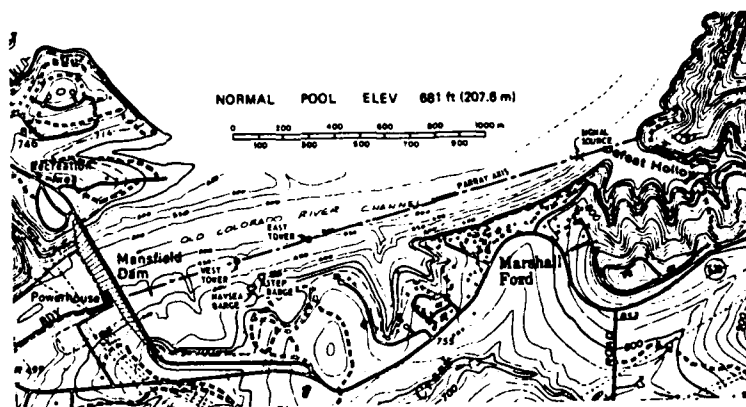
The pump signal was provided by the signal source and power amplifier discussed in the previous section.   Transducers used as pump and hydrophone were arrays of 84 elements of the type shown in Fig. 8 which yields a directivity index of 29 dB at 65 kHz.   The pump source level of 218 dB re 1 $\mu$Pa at 1 m corresponds to an electrical power of 60 W at the transducer.   Spectral purity of the pump signal driving the pump transducer was only 2 dB less than the pump signal source spectral purity shown in Fig. 7.   The band elimination processor described previously was used to detect the signals from the PARRAY hydrophone.

In addition to the PARRAY transducers, an omnidirectional standard transducer was installed on the west tower to permit direct comparison of the low frequency acoustic ambient noise with the output of the 340 m PARRAY.   This permits a direct measurement of the spatial processing gain of the PARRAY in the Lake

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Travis environment.  The output of the PARRAY and the omnidirectional hydrophone were digitally recorded and analyzed to determine system performance.

Our analysis of the 340 m PARRAY at Lake Travis shows that pump electronics were the dominant source of self-noise in the PARRAY at frequencies below 200 Hz. Between 200 and 400 Hz, pump electronic and receiver electronic noise were comparable.  At frequencies above 400 Hz the receiver electronics were the dominant source of self-noise under low ambient noise conditions.  Whether or not self-noise limits the array gain of the PARRAY will be determined by the low frequency ambient noise level.  At higher ambient noise levels the PARRAY is ambient noise limited and the maximum array gain commensurate with the directivity of the PARRAY is obtained.  At low ambient noise levels, self-noise may limit the array gain at higher frequencies.

The acoustic sensitivity of the PARRAY, Eq. (2), was used to convert the voltage at the output of the PARRAY to an equivalent, on-axis plane wave pressure spectrum.  The veracity of this equation was established by calibration with acoustic signals transmitted from the point marked "Signal Source" in Fig. 9.

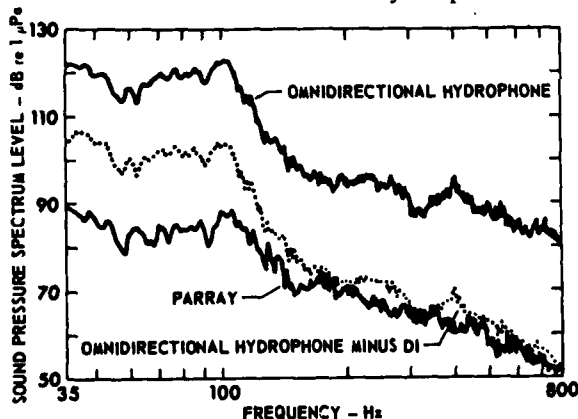The noise pressure spectrum measured with the PARRAY is compared with that from the omnidirectional hydrophone in Fig. 10.  The difference in level between these two curves is the array gain of the PARRAY in that noise environment.  The dotted curve represents the level from the omnidirectional hydrophone reduced by the theoretical DI of the 340 m PARRAY, Eq. (5).  This is a case in which the ambient noise levels are high, especially at the lower frequencies.  It is clear that at frequencies below about 150 Hz the array gain of the PARRAY exceeds the DI by a substantial amount.  At these low frequencies the dominant sources of noise are the generators and spillways in the dam behind the PARRAY. This directly radiated noise is reduced by the back side rejection of the PARRAY, Eq. (6).  Above 150 Hz the

Fig. 10.  Output of 340 m PARRAY and Omnidirectional Hydrophone under Ambient Noise Limited Conditions

noise is more isotropic because noise sources are more distributed and the Lake Travis basin acts like a reverberation chamber.  Under these conditions, the array gain should approximate the DI which is the case for the 150 to 800 Hz region.  The self-noise of the PARRAY is below the baseline of the figure and is an insignificant contributor to the PARRAY output under these conditions.

This same experiment was repeated under much lower ambient noise conditions and the results are shown in Fig. 11.  The ambient noise levels of Fig. 11 represent some of the quietest conditions encountered in Lake Travis.  Note that at frequencies below 120 Hz, the array gain of the PARRAY still exceeds the DI. This is true because the low frequency ambient noise is still dominated by machinery noise from the dam even though power was not being generated. Between 120 and 300 Hz, the ambient noise is more isotropic and the array gain

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approximates the DI. At frequencies above 300 Hz, self-noise limits the array gain of the PARRAY.

At frequencies above 500 Hz the self-noise of this PARRAY is established at 33 dB re 1 $\mu$Pa/$\sqrt{\text{Hz}}$ by the receiver electronic noise. The self-noise of the PARRAY due to sideband noise of the pump signal, Eq. (7), is shown as the thin line segments slightly below the PARRAY output. Note that at lower frequencies the slope of the PARRAY output follows this line but is somewhat higher. This may be the effect of low frequency ambient noise added to the pump sideband noise or it may be the effect of another mechanism, such as pump-boundary interaction. In the 120 to 300 Hz frequency range, the self-noise is a marginal contributor to the ambient noise in the total PARRAY output. It should be clear that improving the spectral purity of the pump signal would reduce the self-noise floor of the PARRAY at low frequencies. It should also be noted that increasing the pump source level will reduce the self-noise floor at higher frequencies.



Fig. 11. Outputs of 340 m PARRAY and Omnidirectional Hydrophone Showing PARRAY Ambient Noise Limited Below 300 Hz and Self-Noise Limited Above 300 Hz

In so far as we could determine, vibration did not affect the self-noise of the 340 m PARRAY during normal operation. However, vibration can be a significant contributor to self-noise as indicated by Eq. (12), especially at low signal frequencies and small pump-hydrophone separations. To test the validity of the analytical model for vibration effects, the electronics from the 340 m PARRAY were used to implement a 5 m PARRAY. Smaller transducers with 19 elements were used and the pump power level was reduced. The PARRAY hydrophone was instrumented with a shaker and accelerometer so that vibration of the hydrophone could be induced and accurately measured while the PARRAY was operating.

The experimental technique involved measurement of the acceleration of the PARRAY hydrophone and transformation of it to an acoustic equivalent by Eq. (12). The result of this measurement and transformation for data obtained while the PARRAY hydrophone was being shaken at frequencies of 146 and 292 Hz is shown in the lower curve of Fig. 12. This represents the on-axis plane wave acoustic signal that would produce the same output voltage from the PARRAY that was generated by the hydrophone acceleration as calculated from Eq. (12). The output of the PARRAY was measured simultaneously and it is shown in the upper curve. At 146 and 292 Hz the levels from the PARRAY are within 2 dB of those predicted from the acceleration measurement. Note that the self-noise floor of the PARRAY is very high under these conditions since the 65 kHz pump frequency is much too low for such a short PARRAY. An independent measurement with an omnidirectional hydrophone located nearby confirmed that the signal from the PARRAY was caused by vibrations and was not due to acoustic signals at 146 and 292 Hz.
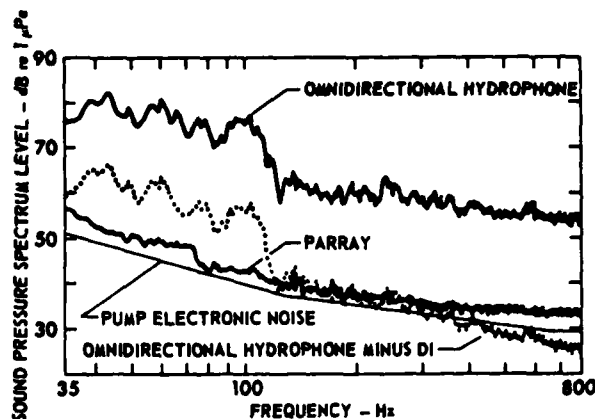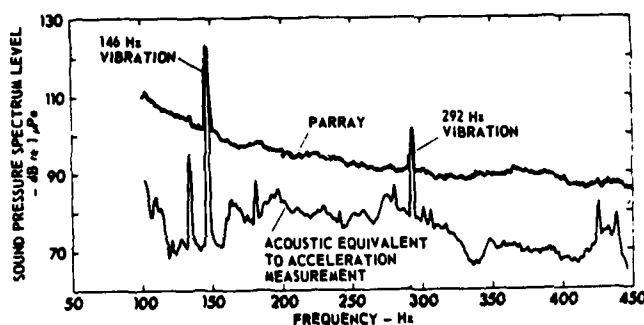
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Fig. 12. PARRAY Response to 146 and
292 Hz Vibration Compared with Acoustic Equivalent of Transducer Vibration
from Vibration Model

The same experiment was repeated several times at various frequencies with similar results. Figure 13 shows the agreement between measured and predicted response of the PARRAY to vibration over the 100 to 700 Hz frequency range. The differences are believed to be primarily due to the difficulty of accurately measuring the transducer front face vibration. However, these results confirm the theoretical model for PARRAY response to vibration.
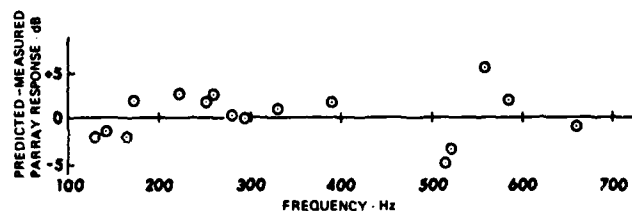


Fig. 13. Comparison of Theoretical and Experimental Response of the PARRAY to Transducer Vibration

## VI. SUMMARY

The PARRAY exploits the inherent nonlinearity in the pressure-density relationship of water to achieve the directional response characteristics of a continuous end-fire array with two small, high frequency transducers and some associated electronics. An analysis of the PARRAY shows that it satisfies the fundamental requirements of an acoustic sensor. This analysis also demonstrates that self-noise is the critical factor for practical utilization of the PARRAY to receive low frequency acoustic signals in the ocean.

The principal self-noise sources in the PARRAY are: pump frequency ambient noise, pump electronic noise, pump and hydrophone vibration, receiver electronic noise, pump-boundary interaction, and pump interaction with medium inhomogeneities. Self-noise of the PARRAY can be expressed as the incoherent sum of the equivalent noise pressures due to these sources. Selection of optimal parameter values for the PARRAY can be accomplished by minimizing the self-noise of the PARRAY within the constraints of existing electronic and transducer technology.

A large aperture PARRAY incorporating state of the art hardware was designed, fabricated, and installed in Lake Travis, Texas, with the transducers located on bottom mounted towers separated by 340 m. Tests were performed to investigate the validity of the system design criteria. These tests verified that the predicted array gain was achieved and that the experimental PARRAY was ambient noise limited over the frequency range from 35 to 800 Hz under almost all conditions encountered in Lake Travis.

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